Effects of Sub-surface Structures and Compositions on Contamination in Groundwater Aquifers in the Midwest

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Abstract

The objectives of this study are to ascertain some of the most common structures and depositional settings in the Midwestern United States and to make suggestions for removal strategies and preventative measures addressed towards reoccurrences. Due to glaciation, the Midwest is mostly composed of unlithified sediments. These rocks have larger pore spaces than lithified rocks, which causes them to be extremely hydraulically conductive. This high conductivity allows for quicker diffusion of contaminants, which is especially prevalent in sand and gravel aquifers. Clays and silts are capable of narrowing down and increasing the speed of flow paths due to being less conductive. The contaminant density is a major part of the ease with which they can flow in the subsurface while remaining difficult to cleanup. Denser-than-water substances will sink to the bottom of a conductive aquifer while lighter-than-water contaminants will rise to the top. Less conductive layers will act as accumulation points for both types of materials as well as flow paths if they are discontinuous or fractured. With the limited number of extraction methods available to cleanup efforts, the best suggestion I can make is to with the original treatment, but to be mindful of the density of the contaminants as well as the geology of the subsurface. Both factors will affect how far down the well will need to be drilled. Lighter contaminants will require a shallower well, whereas denser substances will require deeper wells under relatively homogenous conditions.

Acknowledgements

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Introduction

The objectives of this study are to identify the most likely structures and depositional settings that allow retention of contaminants and to make recommendations for contaminant removal strategies and preventative measures to address the reoccurrence of the problems. Throughout the Midwestern United States, there are regions that contain manufacturing plants for metal fabrication and vehicle manufacture. These corporations sometimes handle hazardous chemicals such as solvents like trichloroethylene (TCE) or tetrachloroethylene, also known as perchloroethylene (PCE), which are effective solvents for cleaning metals. These contaminants are also member of a larger family of contaminants, called "volatile organic compounds" by the Agency for Toxic Substances and Disease Registry (ATSDR). These contaminants are usually costly to remediate once they occur in groundwater and are harmful to the human body, which is why their responsible disposal is monitored by the Environmental Protection Agency (EPA) and the ATSDR. Proper disposal usually entails discarding liquid waste into hazardous waste landfills, to keep them contained for hundreds of years depending on the hydraulic conductivity and subsurface flow paths.

Historical, careless disposal by many companies onsite has caused pervasive contamination of groundwater in industrial areas, especially in the Midwest. Due to the variability of the subsurface settings, cleanup of these zones of contamination can be quite difficult and extremely time-consuming, especially because the geology of the area might allow for a large-scale spreading of the contaminants. My study herein is to identify the various types of subsurface settings that can facilitate expansion of contamination. This includes distinctions between different rock layer compositions and their varying forms. I will also discuss the diverse effects of groundwater flow on contaminant migration.

Geologic Settings

The Midwest is characterized by primarily flat topography with rolling hills and only a few areas exhibiting any large elevation contrasts. These topographic settings are primarily due to the influences of past erosional events on the bedrock (glaciations, down cutting of rivers). Bedrock is typically mantled by unlithified sediments, which are associated mainly with glacial activity ending most recently about 20,000 years ago which can most recently be traced to the glacial periods during the Pleistocene. Till, lake sediments, and outwash are the most common glacial deposits.

The northern states in the Midwest were affected during the most recent glaciation, commonly referred to as the Wisconsinan Glaciation the most recent of the Pleistocene glaciations. The topography and depositional history were also shaped by the glacial events throughout most of the Pleistocene with most of the erosion originating from the earlier Illinoian and other glaciations. Figure 1 provides an example of the differences among these separate events by demonstrating the movement of the glaciers in Wisconsin. The term Pre-Illinoian is used to refer to the earlier glacial periods (Kansan and Nebraskan); but the nomenclature has recently been discredited due to inconsistencies in depositional histories.

Figure 2 is a map of Ohio, showing the glacial deposits and relative ages of deposition during the glacial periods mentioned above. This map illustrates the associations of different sediments as well as also providing a sense of the distances traveled by some of the glaciers. Syverson and Colgan (2004) also pointed out when the last glacial maximum occurred, how glaciers spread throughout most of Wisconsin leaving only a small portion untouched in the central and the southwestern sections of the state. Glover and co-researchers (2011) participated in a similar study for Indiana and Ohio, theorizing that the basins throughout central Indiana and western Ohio were formed during the recent deglaciation.

Environments at Risk for Contamination

Locations that can easily become contaminated tend to be places where near-surface deposits consist mostly of unlithified deposits (like sands and gravels) and/or highly permeable bedrock. These zones occur on most continents but are especially evident in the northern hemisphere associated with glaciated regions. This is the case for the Midwest and is also the focus of this study. As a result, most of the settings discussed in this place are glacial in origin; however, these are by no means the only types existing.

Lenses or layers of sands and silts in glaciated material can form permeable pathways within the subsurface. Low permeability units at depth in aquifers provide sites for the accumulation of Dense Non-aqueous Phase Liquids (DNAPLs). Figure 3 demonstrates a few examples of settings that can cause DNAPLs to pool in these sites. Typically, near surface, low permeability units prevent contamination in a non-glaciated or bedrock zone where glacial deposits are thin or non-existent. However, this doesn't mean that the layers can control contamination indefinitely. Table 1 tabulates the values for hydraulic conductivity of the unconsolidated sediments typically found in glaciated regions. The figure shows that silts and clays are somewhat permeable, meaning that a DNPL plume accumulated over any of these layers will eventually flow through it or fractures. This tends to make late detections far more problematical for cleanups in regions like the Midwest.

Light Non-aqueous Phase Liquids (LNAPLs), like oil and gasoline, accumulate at the top of water tables and are susceptible to being trapped by changes in lithology and changes in the groundwater flow directions. Tables 1 and 2 show some types of lithologies and sediments that can be found in glaciated regions and commonly contaminated by LNAPLs. LNAPLs are capable of using highly permeable layers as pathways preferably following the direction of groundwater flow, but they are more susceptible to changes in water table height. According to Schwartz and Zhang (2003), a rising water table is able to trap an LNAPL plume and concentrate it within the area of increase. Alternatively, a sinking water table will disperse LNAPLs in the location around the lowering level, favoring the direction of flow.

Relatively low permeability layers, such as: silts, shales, and clays, are also capable of attenuating spreading plumes of contaminants. If the layers are continuous, they can act as a buffer between zones between shallow contamination and uncontaminated deeper aquifers. However, if contaminants are disposed of inappropriately in shallow aquifers, plumes develop and spread the contamination. The cleanup of just one plume can require an immense amount of effort. Sometimes, one plume may be removed from the subsurface, but another plume of contaminants may be discovered further down the flow path. Such is the case in Elkhart, Indiana where several solvent plumes were discovered in a heavy industrial area, south of downtown (Frieden and co-staff, 2009). These concepts that affect these changes are the continuity of flow rates, which conserves the discharge in the given area by altering the velocity to allow more or less fluid to flow depending on the differences in the areas, and diffusion (Schwartz and Zhang, 2003).

Faults can also occur in the subsurface and form other permeable pathways for contaminant migration. Sometimes, the fault itself can act as an impermeable boundary, reducing the flow rate of the contaminated groundwater, or completely diverting the direction of flow. Man-made well holes or discontinuous layers are also more than capable of acting as permeable pathways for contaminants. Figure 4 describes a contaminant plume seeping through a faulted and drilled confining layer which is also discussed by Santi, McCray, and Martens

(2005), indicating that they can be used as fluid transport paths, in this instance by DNAPLs. This can cause any number of problems when attempting to remediate the subsurface contamination. This includes: extremely slow cleanup, ineffective pumping strengths and cross-contamination of other aquifers at discharge zones. Cross-contamination in particular can make the cleanup effort even more arduous than usual by spreading the plume into lower aquifer units.

Typical Geological Settings in the Midwest

States like Ohio, Indiana, Illinois, Michigan, and Wisconsin have been glaciated and covered by a varied assortment of sediments, like till or glacial outwash depending on the setting. According to Coogan (1996) and Table 3, glacial till is composed of materials with individual grains smaller than can be seen by the naked eye such as clays and silts to large boulders (the smallest variant being pebbles which start at 2 millimeters). The source of these components can be either local or foreign, from as far north as Canada. Due to their size and thickness glaciers tend to pulverize and grind sediments beneath them before re-depositing them as gravel, sand, clay, or silt layers during glacial retreat. The current topography for most of the northern Midwest was strongly influenced by deglaciation. Specific near-ice margin settings give rise to deposits (e.g., kames, outwash, eskers) that tend to create effective confined and unconfined aquifers because of their permeability and large pores between the grains. As mentioned by Schwartz and Zhang (2003), confining beds created by glaciation are usually comprised of till, the direct placement of loose sediments by the ice. Aquifers are commonly formed by outwash, which is related mostly to the melting of the glacier and the releasing of ice-dams or lakes. These two types of depositional settings provide unlithified deposits, which is another reason that glaciated zones complexity in their settings. Table 1 has an in depth chart for the values of the individual hydraulic conductivities for these looser sediments. With this evidence it can be inferred that unconfined aquifers are at the most risk for contamination due to their usually more permeable nature and direct connection to sources of contamination at the ground surface. Otherwise contaminants are slow to penetrate into and then out of a less permeable confining layer, provided the deposits are continuous enough.

Other than permeable glacial deposits, there are several types of sedimentary rocks that are at risk for contamination. These rocks (such as limestones and sandstones) are less common than till or outwash in the Midwest, mostly being found in the southern sections of the region, but they are still capable of facilitating the spread of contaminant plumes. The most at risk settings are rocks like sandstone, limestone, or other highly porous consolidated materials; fractured rock layers are also very hydraulically conductive (Schwartz and Zhang, 2003). These sedimentary rocks aren't inherently as permeable as sand and gravel outwash but can still act as effective aquifers when they are fractured, displaced, or eroded to form unconformities. Table 2 summarizes the hydraulic properties in conductive and non-conductive rocks. The less porous nature of these sediments compared to their unlithified counterparts also allows them to form or behave as more effective confining layers. Rock units with a relatively low permeability make excellent confining layers, provided they aren't faulted or discontinuous. Examples of these types include: shale, slate, granite, basalt, and other low pore space sedimentary, igneous, or metamorphic rocks. These confining layers can act as basement deposits to keep contamination from escaping into lower layers, similarly to clays and silts but with even smaller pore spaces; they can also act as ceilings.

Common Types of Contaminants

There are many naturally occurring and man-made chemicals that end up as contaminants. Some of these substances do not dissolve in water with which they are referred to as DNAPLs and LNAPLs (or just NAPLs). According to Schwartz and Zhang (2003), both types are miscible in water and DNAPLs will always flow downhill once they come in contact with a low permeability layer, LNAPLs being less dense than water will always float on the top of water table.

TCE is currently used as a degreaser for metal parts as well as an extraction solvent for many organic compounds including oils and greases while PCE is commonly used as a dry cleaning agent, according to the descriptions in the Toxic Substances Portal of the ATSDR's website. Both are industrial chemicals that can be treated as DNAPLs due to their tendency to sink in groundwater. As such, they are much more difficult to remove from the subsurface because their detection is often long after they have penetrated to a depth with a high enough concentration that the full extent of spreading can't be calculated easily. Gasoline or other forms of hydrocarbons, which are used as various fuels, are examples of LNAPLs. These substances are less dense than water and tend to float above the water table or stopping and pooling at impermeable boundaries. They tend to be mobile if they are released underground but LNAPLs are far easier to remove from the groundwater because they are found at shallow depths.

Other common contaminants are usually naturally occurring in the subsurface and are the results of reactions between fluids in the rock layers and the minerals within them. This process, which uses fluids of varying levels of acidity, is referred to as dissolution and is discussed in greater detail with differing examples of fluid and contaminant composition in the similarly named section in Schwartz and Zhang (2003). Sulfuric acid, arsenic, methane, chloride, alkaline salts and other such substances can be formed or dissolved by fluids (such as water) reacting with those minerals and are able to follow groundwater flow. This is discussed in even further detail in the article by Metcalf and Robbins (2013), where the researchers went into extensive detail on the effects of dissolution into the groundwater of developed/developing areas. The article deals with the influences of both naturally occurring and human induced substances into the subsurface water column as well as the effects pumping and layer composition may have on the concentrations. In the case of naturally occurring substances, the fluids will usually dissolve the minerals and, if given enough time and the proper environmental conditions, may eventually precipitate them out again. Some of these contaminants are non-aqueous but a large portion of them are water soluble and therefore susceptible to dissolution.

Discussion

The possibility of contamination of confined or unconfined aquifers differs from region to region with a correspondingly large number of factors. To limit the perspective, I used the Midwestern United States in an effort to reduce the overall variables. The primarily glaciated nature of its topography and similarity in the types of aquifers allows the architecture of these units. Groundwater flows quickly through more permeable units with these units of concern tending to be glacio-fluvial aquifers and fractured bedrock (see tables 1 and 2 for hydraulic conductivities). Due to this speed, contamination will spread fairly quickly, forming large plumes down gradient from DNAPL sources, provided there is continuity in sand layers or for example: faults or permeable unconformities. Van der Pluijm and Marshak (2004) provide examples for unconformities and faults, all of which can affect the aquifer's susceptibility to contamination.

Aside from the speed of groundwater flow; the pore size of sediments is an important factor in contamination transport, which affects the transport velocities. The larger the pore spaces, the more fluids and/or contaminants that can be stored inside the rock. Conversely, rocks with smaller pores are commonly less permeable making it more difficult for contaminated groundwater to enter. Ideally, to improve permeability, a sedimentary layer needs to have large pore spaces, which usually means the unit needs large grains. As such, between the glaciated and non-glaciated sediments, unlithified sand and gravel have the greatest permeability because they have the largest spaces between grains (as well as the largest grains). This means that these layers are at the highest risk of contamination diffusion.

Many aquifers in the Midwest are composed mostly of unconsolidated gravels, sands, silts, and clays. They are capable of transporting and diffusing contaminants at a much faster rate than lithified bedrock. It can then be inferred that the more water soluble a substance, the faster it flows in groundwater with the maximum flow speed being equal to water flow velocity. As such, many insoluble industrial chemicals leaked into these aquifers tend to move at a slower rate when compared to their naturally miscible counterparts, which also slows down the speed of diffusion. This makes them easier to detect, but more difficult to remove due to the differences in depth in the water table because of the density discrepancies.

Low permeability and faults are examples of two types of features found in the subsurface that can influence groundwater flow. They are capable of altering the direction of flow in water using lenses, basins, synclines, domes, anticlines, and unconformities from low permeability rock that can accumulate the immiscible solutions. They can also cause increases in groundwater velocity due to the property of water to move around most of these impermeable obstructions while maintaining the volume of water moved over any length of time. This would be troublesome to detect unless the testing wells are placed above these resistant layers. These forms of interference would require an increase in the amount of time that pumping would need to continue to remove the contaminants. These structures are more common in highly eroded locations, especially in glaciated regions. However, these are in no way only indicative of the Midwest in that most if not all glaciated regions in the northern hemisphere share these similar characteristics.

Conclusion

Containing the spread of contamination requires low permeability subsurface settings, promoting the diffusion of the plume. It requires that the primary sediments the substance has infiltrated be more permeable than these obstructions and that flow is strong enough to move the pollutants outside of pumping range. The most commonly used method currently for removing contamination is pump-and-treat. The most effective way to monitor a contamination plume is to calculate the flow rate of the groundwater, find the direction of the flow path, determine the density of the contaminant, and then test wells within the area of effect. It also helps to understand the local geology and the hydrogeologic setting. This is especially important in the Midwest due to the glaciated nature of its sediments, which can rapidly progress contamination due to their permeability, and the industrialized nature of certain areas in the region.

Suggestions for Future Research

The most effective method to removing contamination plumes we currently have is to use water pumps to draw the pollutants out of the groundwater. There have been many instances where, thanks to the layout of a city's aquifer and the locations of their pumps, their drinking water becomes contaminated due to the rate of diffusion of the plume. While pumping is definitely effective, I've often wondered if there was any way to slow down the plume's rate of advance or to seal off a leaking confining bed that a plume managed to infiltrate; if not at least for the short term. With this in mind, I wanted to suggest future research in the effects interactions between different types of contaminants in groundwater have on decreasing the rate of diffusion of contaminant plumes. I would also like to suggest looking into the effects that some substances have on sealing leaking confining beds.

Tables

Hydraulic conductivity of unconsolidated materials

Grain-Size Class	Hydraulic Conductivity (m/day)					
	Degree of Sorting			Silt Content		
	Poor	Moderate	Well	Slight	Moderate	High
1. Fine-grained Materials						
Clay	0.0003					
Silt, clayey	0.3–1.2					
Silt, slightly sandy	1.5					
Silt, moderately sandy	2.1–2.5					
Silt, very sandy	2.7–3.5					
Sandy silt	3.4					
Silty sand	4					
2. Sands and Gravels						
Very fine sand	4	6	8	7	6	4
Very fine to fine sand	8	8	—	7	6	4
Very fine to medium sand	11	12–14	—	10	8	6
Very fine to coarse sand	15	—	—	12	9	7
Very fine to very coarse sand	18	—	—	16	12	9
Very fine sand to fine gravel	23	—	—	20	16	12
Very fine sand to medium gravel	30	—	—	24	20	15
Very fine sand to coarse gravel	39	—	—	33	26	20
Fine sand	8	12	16	10	8	6
Fine to medium sand	16	20	—	15	12	9
Fine to coarse sand	17	20 – 22	—	16	13	10
Fine to very coarse sand	21	—	—	18	14	11
Fine sand to fine gravel	27	—	—	23	18	13
Fine sand to medium gravel	35	—	—	29	23	17
Fine sand to coarse gravel	44	—	—	33	27	22
Medium sand	20	24	29	20	16	12
Medium to coarse sand	23	29	—	22	17	13
Medium to very coarse sand	26	30–34	—	22	19	15
Medium sand to fine gravel	31	—	—	26	21	16
Medium sand to medium gravel	40	—	—	35	25	20
Medium sand to coarse gravel	50	—	—	41	33	25
Coarse sand	24	33	41	29	23	16
Coarse to very coarse sand	29	41	—	29	23	17
Coarse sand to fine gravel	35	41–48	—	33	27	21
Coarse sand to medium gravel	45	—	—	35	29	23
Coarse sand to coarse gravel	56	—	—	41	30	28
Very coarse sand	33	45	57	35	29	23
Very coarse sand to fine gravel	41	65	—	37	32	27
Very coarse sand to medium gravel	52	61–69	—	45	37	30
Very coarse sand to coarse gravel	63	—	—	49	40	32
Fine gravel	49	65	81	69	43	33
Fine to medium gravel	61	102	—	61	51	41
Fine to coarse gravel	75	88–102	—	71	58	44
Medium gravel	73	70	122	73	61	49
Medium to coarse gravel	90	143	—	90	74	58
Coarse gravel	102	143	183	102	87	71

Source: Lappala (1978).

Table 1: Table of hydraulic conductivities for unconsolidated sediments which can usually be found in glacial drift. (Schwartz and Zhang, 2003)

Representative values of porosity and hydraulic conductivity for sandstone and shale. Other sedimentary rocks are provided for comparison

Lithology	Formation or Geologic Age	Location	Porosity (%)	Hydraulic Conductivity (m/s)	Source
Sandstone	Paskapoo	Alberta	—	4.11×10^{-5}	a
Sandstone	Paskapoo	Alberta	—	2.53×10^{-5}	a
Sandstone	Wilcox	—	—	4.55×10^{-5}	a
Sandstone	Bradford	—	14.8	2.59×10^{-8}	a
Sandstone	Berea	—	19	3.67×10^{-6}	a
Sandstone	Pennsylvanian	Illinois	19	1.7×10^{-6}	b
Sandstone	Chesterian	Illinois	17	1.3×10^{-6}	b
Sandstone	Ancell	Illinois	16	4.8×10^{-6}	b
Sandstone	Mt. Simon	Illinois	12	7.4×10^{-6}	b
Mudstone	Cenozoic	North Dakota	—	4.41×10^{-10}	a
Shale (fractured)	Paskapoo	Alberta		3.10×10^{-5}	a
Shale	Graneros	Kansas	11.6	4.51×10^{-13}	a
Shale	Wolfcamp	Texas	—	9.21×10^{-13} (hor.) 9.21×10^{-14} (vert.)	a
Shale	New Albany	Illinois	1.5	1.9×10^{-8}	c
Limestone	Mammoth Cave	Illinois	14	3.7×10^{-6}	b
Limestone and dolostone	Hunton	Illinois	14	1.3×10^{-6}	b
Dolostone	Ottawa	Illinois	8	1.3×10^{-7}	b

[a] Davis (1988).
[b] van Den Berg (1980).
[c] Kalyoncu et al. (1978).

Table 2: The table shows the hydraulic conductivities and porosities of consolidated rocks with varying differences in location and condition of the layers. (Schwartz and Zhang, 2003)

NAMES FOR SILICICLASTIC SEDIMENTS AND ROCKS

Particle name	Particle size	Rock name
pebble or larger	>2 mm	conglomerate if fragments are rounded, breccia if fragments are angular
sand	1/16-2 mm	sandstone
silt	1/16-1/256 mm	siltstone (particles barely discernible; has gritty feel)
clay	<1/256 mm	shale or clay shale if laminated, claystone if massive (particles not discernible; has smooth feel)

Table 3: Basic names and particle sizes for most forms of rock grains as well as applicable common rock names. (Coogan, 1996)

Figures

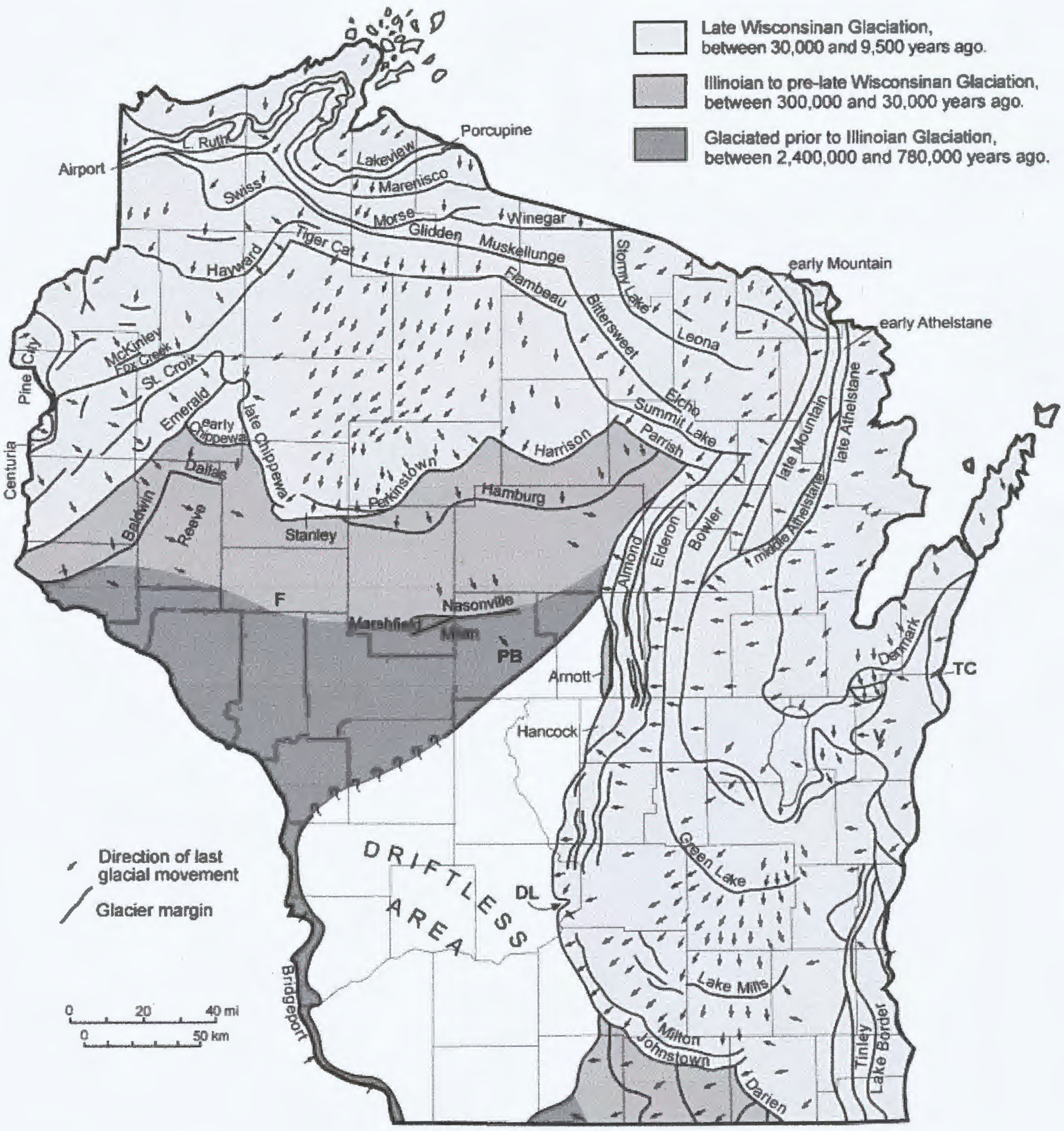

Figure 1: Map of glaciations periods in Wisconsin from the Pre-Illinoian to the Wisonsinan. (Syverson and Colgan, 2004)

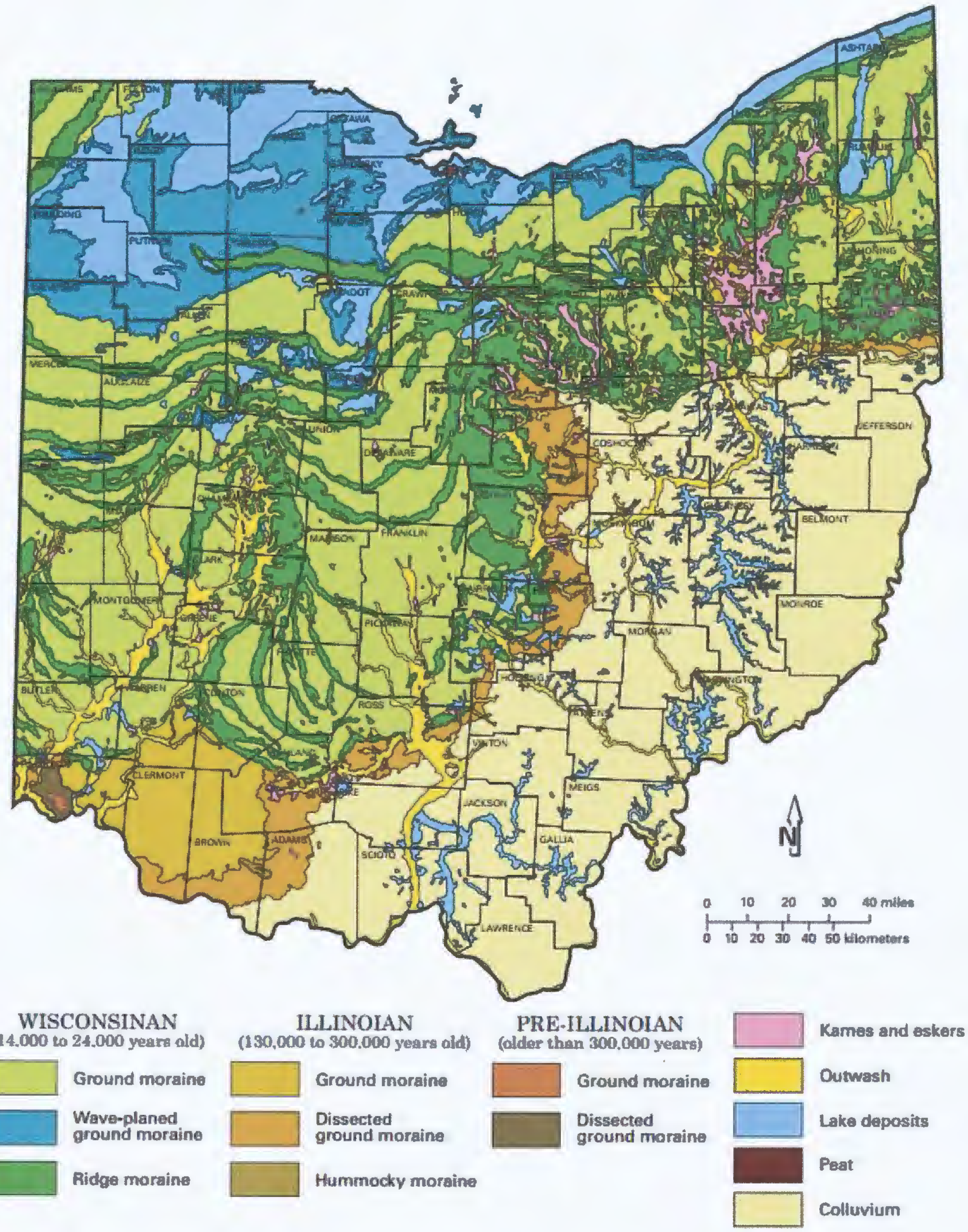

Figure 2: A map of glacial deposition for the state of Ohio including type and relative age of sediments. (Coogan, 1996)

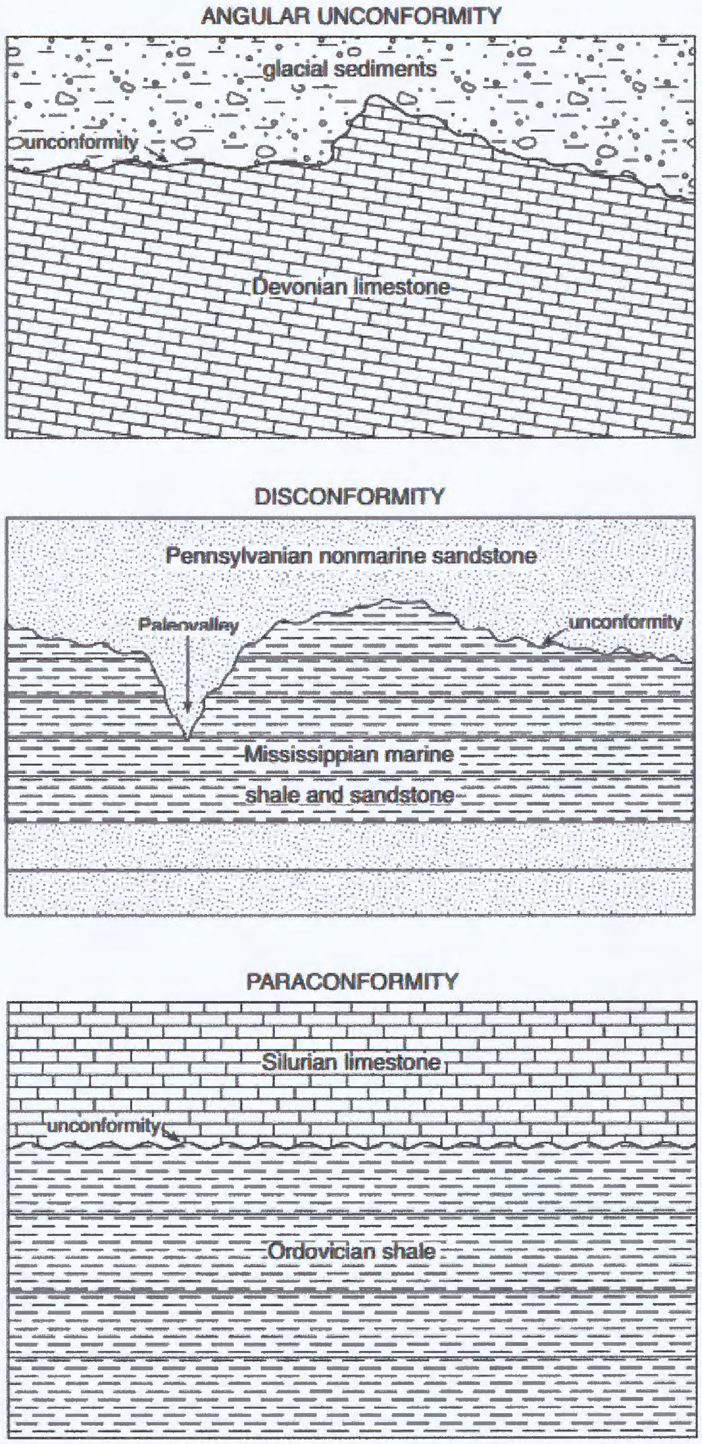

Figure 3: Showing the different types of unconformities. This also demonstrates how unconformities can form traps depending on porosity (Coogan, 1996)

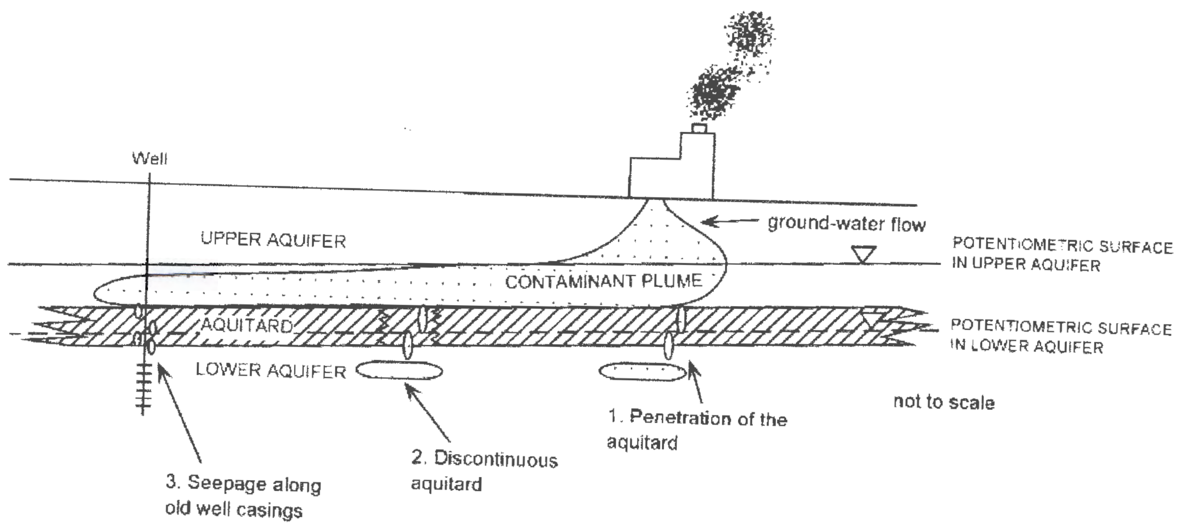

Figure 4: Depicts the behavior of a contamination plume underlain by a leaky confining layer. (Santy, McCray, and Martens; 2005)

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